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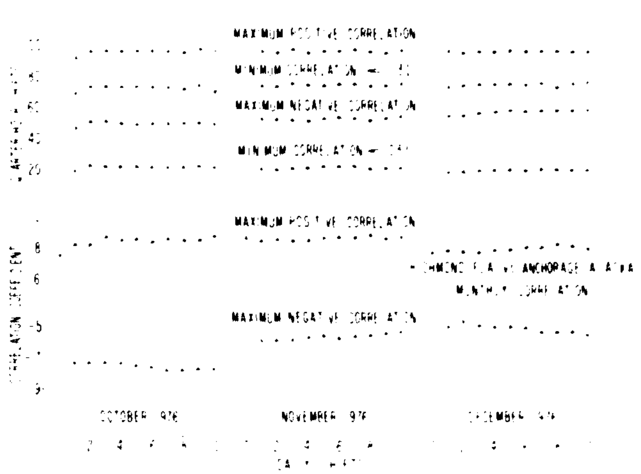

Fig. 1. Variation of positive maxima, negative maxima, and minima of correlation coefficient of Anchorage, AK, and Richmond, FL, monthly data sets with respect to daily time shifts. Also indicated are corresponding quarter-hour time shifts for which these were attained. Analysis was made for October, November, and December 1976.

(6) Correlation of Satellite Signal Time Delays at Widely Separated Locations

(10) HAIM SOICHER

Abstract—**A correlation analysis of ionospheric signal time delays performed for nearly co-longitudinal locations is extended to widely separated locations. Monthly and daily maximum correlation coefficients were in general 0.8.**

INTRODUCTION

Signal time delays, or equivalently, range errors in radar and/or satellite navigation systems, are always encountered in transionospheric propagation due to the fact that the electromagnetic propagation velocity in the ionosphere is slightly less than the free-space velocity [1]. For frequencies above ~50 MHz, this excess time delay is inversely proportional to the square of the frequency and is directly proportional to the integrated electron density, i.e., total electron content (TEC), along the propagation path. The TEC may be determined by forecasting techniques based on media models [2], [3]. Due to the spatial and temporal variability of the ionospheric electron density, forecasting accuracy could be improved by periodic updating of the TEC (preferably in real time) at specified locations. The question arises as to the extent of the geographic area surrounding a station having real-time TEC determining capabilities, within which TEC values could be interpolated with acceptable accuracy.

In a previous paper [4] the correlation between TEC values at Fort Monmouth, NJ, (40.18 N, 74.06° W) and Richmond, FL, (25.60° N, 80.40° W) was determined. The paper concluded that the specific results for the Fort Monmouth–Richmond locale separation, i.e., the high correlation obtained for the TEC, should allow accurate interpolation of the TEC at one of the stations from its real-time measurement at the other. It was indicated that similar analyses would be performed at stations with wider geographical separations.

To this end, a specific investigation designed to determine the correlation between TEC values at Richmond, FL, and Anchorage, AK, (61.04° N, 149.75° W) was undertaken. The TEC was determined by means of the Faraday rotation technique using beacon transmissions of the geostationary SMS 2 satellite (located at 136° W).

The subionospheric points for the two stations (i.e., the geographic locations where the ray paths to the satellite intersect a "mean" altitude of 420 km) were 23.3° N, 88.1° W for Richmond and 54.3° N, 146.5° W for Anchorage. Thus, the "representative" TEC for the two stations was separated by ~31° in latitude and by ~58° in longitude (corresponding to a 3-h 53-min difference in local times). The analysis was performed for the last three months of 1976.

THE DATA

The correlation analysis performed was computed in two ways: in monthly intervals and in daily intervals [4]. For the former way, a full month's TEC values for Anchorage were correlated with a full month's TEC values for Richmond. For the latter way, data sets for both locations were correlated on a daily-interval basis. In both cases the Anchorage data were shifted at the outset so that both data sets corresponded in local time.

The monthly correlation analysis for October, November, and December 1976 is summarized in Fig. 1. Indicated in this

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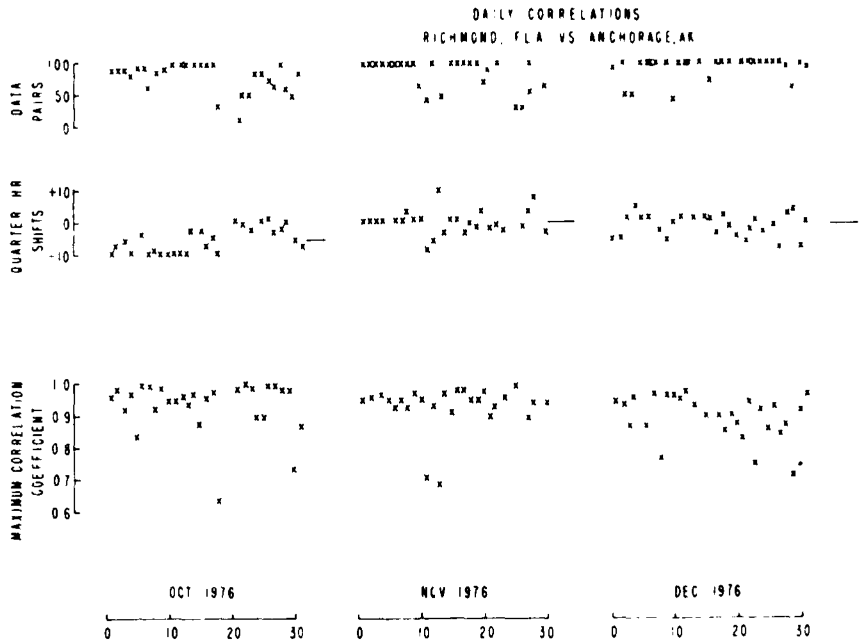

Fig. 2. Variation of maximum correlation coefficients at Anchorage, AK, and Richmond, FL, daily data sets. Also indicated are time shifts for which these were attained, their averages (- - -), and the number of data pairs used in the analysis.

figure are the positive maxima of the correlation, the negative maxima of the correlation coefficient (obtained by continuously time-shifting the data at Anchorage by 15-min intervals in the forward direction with respect to the data at Richmond (see [4])), and the corresponding time shifts for which these maxima were obtained. These time shifts are plotted as daily shifts, since the correlation coefficients maximize (positively or negatively) at 24-h intervals. Also indicated are the time shifts that correspond with minimum correlation ($<|0.03|$).

For the indicated months, the positive maximum of the correlation coefficient was not the highest for corresponding data sets (i.e., data shifted only to correspond in local time (first point on graph for each month)). The maxima of the correlation coefficients was in general $\gtrsim 0.8$ for up to 10 day shifts. Successive maxima obtained by shifting the two data sets by approximately 24 h remain nearly constant in absolute value. All this is in contrast to the reported Richmond–Fort Monmouth TEC correlation [4], where the no-shift correlation was highest ($\gtrsim 0.9$) and succeeding maxima declined. In general, the maximum negative correlation was lower than the maximum positive correlation in absolute value for all reported months. The maximum negative coefficient was highest in October and declined monotonically in the succeeding months.

The day-to-day maximum positive correlation coefficients for October, November, and December 1976 are shown in Fig. 2. These were arrived at by comparing the Richmond and Anchorage data at 15-min intervals for each day of these months. Starting each day at the same local time the Anchorage data were then shifted with respect to the Richmond data at 15-min intervals in the forward (+) direction and in the backward (−) direction. The number of shifts for which the coefficients are maximized is also shown in the figure, in addition to the number of data pairs available for the correlation for each day (maximum of 96 data pairs).

In general, the coefficients ranged from ~0.8 and ~1.0 with relatively few falling below 0.8. The bulk of the coefficients was above 0.9, which was the range of the Richmond–Fort Monmouth data. The correlation coefficient was, on the average, higher in October, declined in November, and declined further in December. This was undoubtedly due to the sunrise and sunset times at both locales. In mid-October the sunrise and sunset times (at 400 km) at the subionospheric points differed by about 15 min, while in mid-December they differed by about 45 min. Thus in December the shape of the diurnal variation curve was considerably different for the two locales than that in October. The result is a decrease in the magnitude of the correlation coefficients. On the average the coefficients were maxima at ~−5 shifts in October, no shifts for November, and ~−2 shifts for December.

CONCLUSIONS

The data reported here indicate that TEC, or equivalently, ionospheric signal time delays, are highly correlatable despite the very wide separation (31° in latitude, and 58° in longitude) of the two stations. The monthly correlation exhibits a seasonal effect, but within any one month the correlation remains nearly constant despite shifts of one data set with respect to the other. The daily correlations also exhibit a seasonal effect, mainly due to changes in TEC diurnal shapes associated with changing separation in sunrise and sunset times at the two locales.

It appears that continuous TEC data at one locale may be used to forecast a continuous data set at the other locale (provided some corresponding data are available at the other locale) so that the two data sets will be correlated with a coefficient of > 0.75. Further, daily TEC values at one locale may be ascertained at any time from a short-term (1 day) known current variation of TEC at the other locale. The specific results for these widely separated locales give credence to the possibility of TEC forecasting, the alternative mentioned in the Introduction, whereby a satellite navigation system using one frequency could provide accurate ranging information by correcting for ionospheric errors.

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